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Jon Sinnreich[1]

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Optimizing the Arrangement of Strain Gauges in Pile Load Testing

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TECHNICAL NOTE

Jon Sinnreich[1]

Optimizing the Arrangement of Strain Gauges in Pile Load Testing

Reference

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ABSTRACT

The use of strain gauges in a deep foundation element static load test is a common technique to obtain soil strata mobilized resistance. The typical arrangement is several gauges at each of several discrete depths. The gauges at each depth are averaged, the average is converted to a force, and the forces at various depths are differentiated to compute force dissipation into the soil. A simple error analysis leads to the optimal arrangement of gauges in the element cross section, accounting for uneven distribution of strain across the cross-section plane of the element and the possibility of gauge malfunction. By using a case history as an example, the optimal vertical spacing of gauge levels is discussed.

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[1] Load Test Consulting, Ltd., 4203 NW 15th Place, Gainesville, FL 32605, USA, e-mail: jon@ltc-us.com, https://orcid.org/0000-0001-7820-6939

Keywords

strain gauges, foundation load testing, reliability

Nomenclature

ε = Microstrain recorded by a strain gauge.

λ = Mortality rate (probability of failure) of an individual strain gauge.

S_n = Probability of success of a level of strain gauges; that is, the probability that n number of gauges installed symmetrically around the perimeter of a pile's reinforcing cage at a given depth all function properly, and the strain at the pile centroid is computed from their average.

d = Normalized difference between an individual strain gauge reading and the average of all gauge readings at a given level.

α = Angle between independent opposed pairs of strain gauges. Optimally, equal or near to 90° but may be adjusted based on physical configuration of reinforcing steel cage.

Introduction

Strain gauges are routinely used in deep foundation load testing to measure the strain distribution within the foundation element. Data from gauges installed at discrete depths, often an average of multiple gauges positioned around the reinforcing steel cage perimeter, are converted to force in order to assess the resistance of various soil strata. Once cast into concrete or affixed to steel, gauges cannot be repositioned or repaired. Because of cost constraints, the number and position of gauges used in a load test need to be carefully considered to maximize the information gathered from the test as well as for redundancy to compensate for malfunctioning gauges.

This article uses a case history of a bridge structure pile testing program carried out by the author to provide some real-world statistics on strain gauge mortality and to illustrate the optimal distribution of gauges in a pile. The specific pile testing program included seven bidirectional static load tests (ASTM D8169/D8169M-18, *Standard Test Methods for Deep Foundations under Bi-directional Static Axial Compressive Load*), and one lateral load test (ASTM D3966/D3966M-07, *Standard Test Methods for Deep Foundations under Lateral Load* (Superseded)) with installed sisterbar vibrating wire strain gauges. All of the piles were installed using the augered cast-in-place (ACIP) method. The axial test piles were nominal 760 mm in diameter and averaged 35 m deep. The owner of the project specified that for the axial piles, three strain gauges were to be installed per level with spacing between levels of 1.5 m.

Horizontal Arrangement

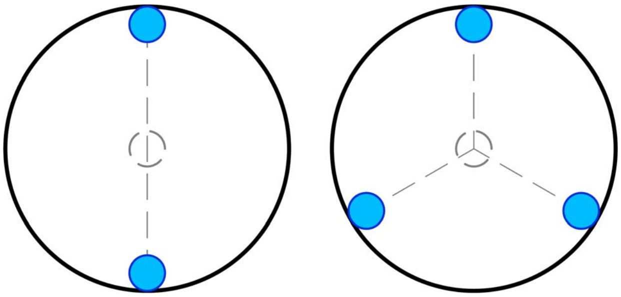
The plane-strain condition is a key assumption of the conversion of measured strain to axial force. Any bending in the foundation element, whether because of eccentric loading, irregular soil resistance, nonuniform cross-sectional area, or any other reason will cause an uneven distribution of strain in the cross section. According to Euler beam theory, the total strain will be a superposition of axial strain (in which we are interested) and bending strain (which for the purposes of an axial load test data analysis is disregarded). The analysis in this article pertains particularly to axial compressive load testing of foundations (ASTM D1143/D1143M-07(2013)e1, *Standard Test Methods for Deep Foundations under Static Axial Compressive Load*, and ASTM D8169), with a presumption that axial strains that are due to applied loading will be compressive and significantly greater than incidental bending strains induced by load eccentricity, etc. Assuming net strain that is due to bending is not enough to cause tension cracks anywhere in the cross section, total strain is assumed to be linearly distributed across the plane of the element, and the net average axial compressive strain corresponds to a line that is transverse to the long axis of the element, aligns to the axis of bending, and intersects the centroid of the element. Therefore, obtaining the strain at the centroid is key to computing the net axial force.

Typically (if the steel reinforcement permits), two or more strain gauges per level are installed in a test foundation. This arrangement allows for an estimate of the strain at the centroid of the element to be computed as an average of the individual strain measurements. A single opposed pair is the most common arrangement. In the case history test program discussed herein, the owner specified three gauges per level. Although it was not explicitly specified, the implied arrangement was an equal spacing of 120° around the perimeter of the pile reinforcement cage (**fig. 1**).

Strain gauges installed within cast-in-place piles in the field have a relatively high probability of failure λ. This is typically because of installation procedures for deep foundations. For drilled shafts, heavy rebar cages must be picked by a crane, tilted from horizontal to vertical, and then inserted into the excavation. Concreting then takes place, either via the tremie method or by gravity pour, either of which is a dynamic process with plenty of opportunity to damage a gauge. For ACIP piles, the rebar cage is typically lifted at the head only for insertion into the wet grout. This necessitates inducing a bend into the cage, followed by rapid insertion of the cage into grout under self-weight. In the case history testing program, from a total of 492 sisterbar vibrating wire strain gauges installed in eight test piles, thirteen failed to function during testing, for a λ of 2.6 %.

FIG. 1

Typical arrangement of opposed pair and triplet strain gauges in pile cross section with computed average (dashed lines).



In order to compute the average strain at the centroid of the pile cross section, the gauges at a given level must be arranged symmetrically. If there is no redundancy with independent opposed pairs of gauges, then all the gauges at a given level must function. Given n gauges at a level, the probability of success in this situation is computed as the simultaneous probability of survival of all the gauges:

$$S_n = (1 - \lambda)^n \tag{1}$$

Although in practice if a single gauge fails the remaining gauge(s) are often still used to measure the strain, this is a suboptimal solution because the resulting average is now away from the centroid and thus may not be representative if an uneven strain distribution is present in the cross section.

To assess the potential magnitude of the difference between using an opposed-pair average and the value of a single gauge (assuming its opposite malfunctioned), data from a total of 144 pairs of functioning opposed gauge pairs in seven axial test piles in the case history are analyzed. A relative difference is computed for each logged reading of each opposed gauge pair:

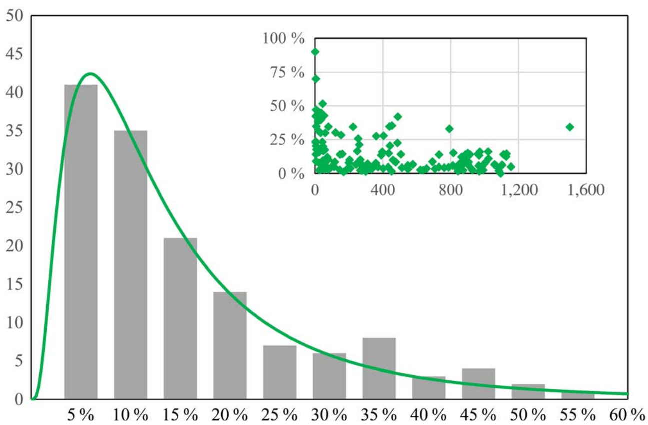
$$d = \frac{|\varepsilon_1 - \varepsilon_{Avg}|}{\varepsilon_{Avg}} \quad \text{where} \quad \varepsilon_{Avg} = \frac{\varepsilon_1 + \varepsilon_2}{2} \tag{2}$$

For each gauge pair, the differences are averaged for all increments of loading. The resulting 144 data points are plotted on a histogram, and a log-normal probability distribution function is fitted to the resulting data (fig. 2).

The results of this analysis indicate that for this particular data set, the mean difference between data from a single gauge and the average of an opposed pair is 15.2 %, a significant dissimilarity. The inset figure plots the

FIG. 2

Histogram and estimated probability distribution for percent difference between individual and averaged strains (inset figure—percent difference versus maximum average strain).



percent difference between individual and averaged strains versus maximum average strain, which ranged from single digits of microstrain in gauge levels near the ground surface to over 1,000 microstrain in the vicinity of the bidirectional jacks. Although several of the highest individual difference values correspond to the smallest maximum strains, overall, there is a fairly even distribution and no strong correlation to absolute values of strain, indicating the high mean difference is not confined to gauge levels recording relatively little strain. Obtaining a good measure of the average strain, rather than relying on an off-center result, is thus crucial to computing the force distribution in the foundation.

Using equation (1), the counter-intuitive result is obtained that installing three equally-spaced gauges per level (presumably for redundancy) results in a lower probability of successfully obtaining the average strain at the pile centroid (92.3 %) than using two gauges in an opposed pair (94.8 %, using the numeric values for our case history). This is because in either arrangement, the average strain at the centroid is not obtained if one gauge is lost, and assuming each individual gauge has an equal probability of malfunction, there is a higher cumulative probability of losing one gauge out of three installed than one out of two installed.

Recognizing this paradox, the author chose to install the three specified gauges at 0°, 90°, and 180° around the rebar cage at each level (see **fig. 3**). The gauge at 90° position was logged, but the data were not used in the analysis of results unless one of the other gauges malfunctioned. This resulted in a slight improvement in the overall test; 5 of the 13 malfunctions were gauges at the 90° position, resulting in no effect on the data analysis.

A significant improvement in redundancy can be achieved by installing four strain gauges per level if they are treated as two independent sets of opposed pairs. If all gauges function, then the average strain is computed from all four. However, if any one gauge malfunctions, that pair is discarded and the average is computed from the remaining opposed pair only, which should still yield a good measure of strain at the pile centroid. Note that the gauges do not have to be spaced at 90° angularly; each pair needs only to be 180° opposed (**fig. 4**). Recognizing this provides flexibility when selecting gauge locations around the reinforcing cage.

FIG. 3

Strain gauge triplet averaging results with defective gauge (left), and with 0°, 90°, and 180° arrangement (right).

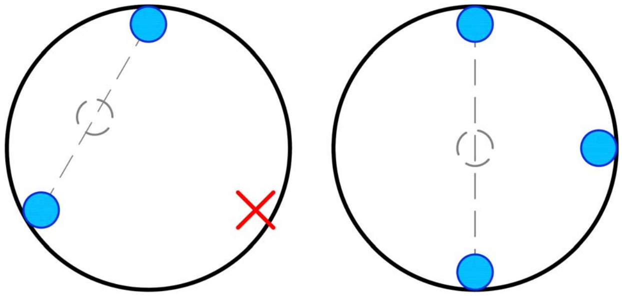
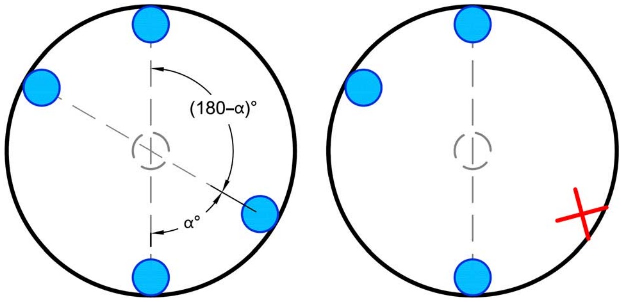


FIG. 4

Averaging results for two opposed pairs of strain gauges.



The probability of success (S_{2x2}) for this arrangement is computed as one minus the probability of simultaneous failure of both opposed pairs:

$$S_{2x2} = 1 - (1 - S_2)^2 = 1 - (1 - (1 - \lambda)^2)^2 \tag{3}$$

For our case history, using the same value λ of 2.6 % results in a probability of success of 99.7 % (up from 94.8 % using two gauges in a single opposed pair).

Vertical Arrangement

The specifications for our case history called for strain gauge placement every 1.5 m (5 ft). In piles that were an average of 35 m deep, this resulted in more than 20 levels of gauges per pile. It is likely that this specification was created long before detailed soil boring logs were available, in an attempt to assure adequate information was collected. **Figure 5** illustrates the soil boring log for one test pile, along with a superimposed force distribution from the maximum load increment and the resultant unit shear (*t-z*) curves generated from the 24 layers of embedded strain gauges (solid lines, right side of figure). Note that this figure is for illustrative purposes only—scales and magnitudes are not included.

FIG. 5 Case history stratigraphy, force distribution, and *t-z* curves (soil boring log courtesy of Universal Engineering Sciences, Inc.).

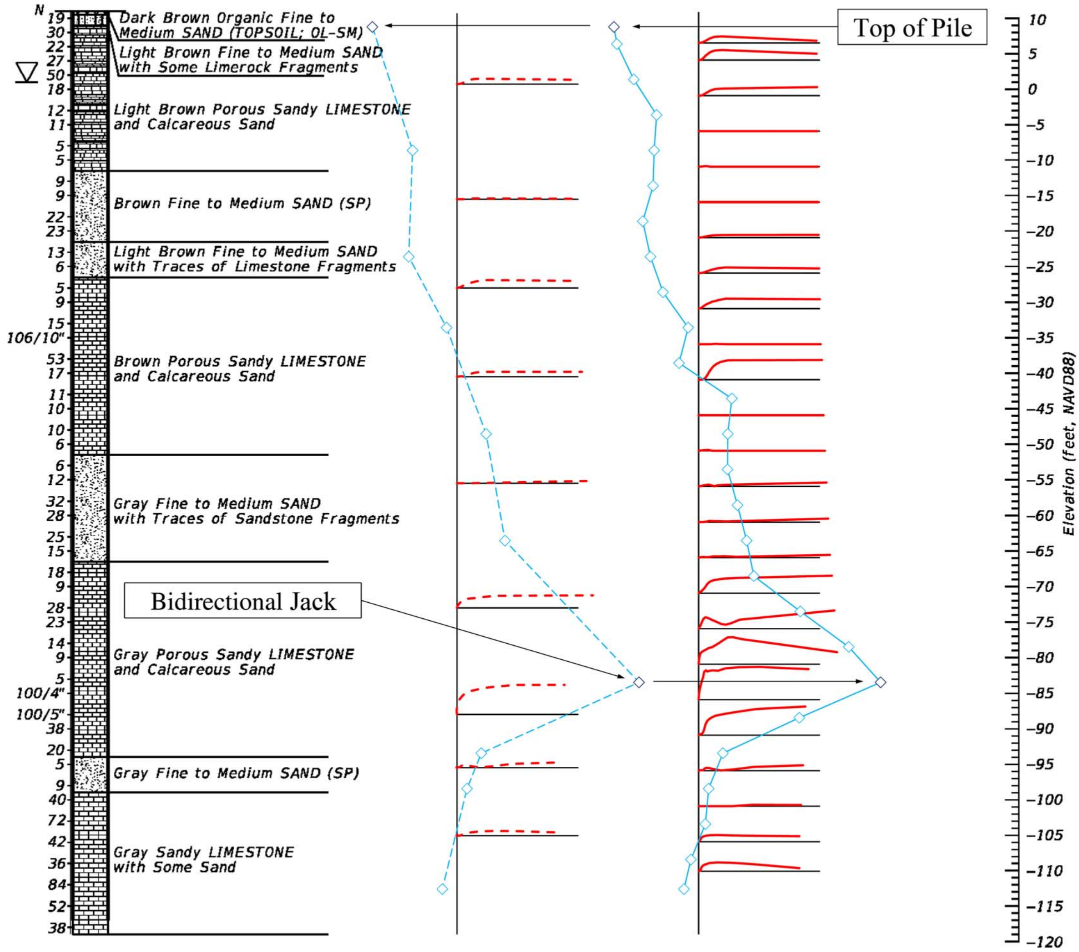
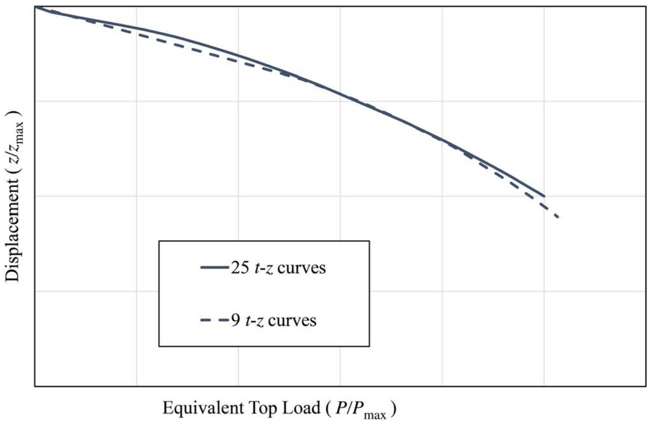


FIG. 6

Equivalent top load curves generated from 25 and 9 *t-z* curves.



The only two points of known force are the bidirectional jack itself (force generated by applied pressure) and the ground surface/top of pile (zero load). Conversion of strain gauge data to force was achieved using the nonlinear stiffness method (Sinnreich 2012). Despite a detailed analysis of data at every gauge level, which included an assessment of pile diameter at each gauge level based on Thermal Integrity Profiler data (ASTM D7949-14, *Standard Test Methods for Thermal Integrity Profiling of Concrete Deep Foundations*), certain gauge levels (most notably at an elevation of −38.5 ft) yielded a force that was higher than the gauge level below (closer to the embedded bidirectional jack)—an impossible result. This is likely due to some combination of the limitations of the pile modulus estimate, pile cross-sectional area estimate, alignment of the individual gauges within the pile (verticality), and the localized quality of grout and grout bond to the sister bar. Conversion of strain into force in pile tests involves many assumptions and uncertainties, regardless of the specific conversion method chosen (Komurka and Moghaddam 2020). Strain gauges in pile testing are not high-precision instruments, and spacing them this closely can reveal their limitations, which can be thought of as "noise" in the calculated force "signal."

In addition to determining unit shaft resistance values, the purpose of strain gauges in many instances (and in this particular case) is to generate or validate, design *t-z* curves. As a thought experiment, two-thirds (16 of 24) of the gauge levels were eliminated from the data set, using the on-center soil boring log as a guide. Only the bottom-most gauge level, gauge levels nearest soil strata interfaces, and some intermediate levels were retained, leaving a total of eight levels of gauges in the test pile (**fig. 5**, dashed lines in middle of figure). The resulting internal force distribution and *t-z* curves, although not as detailed as the full data set, nevertheless convey the necessary information to perform a top-down load-settlement analysis. Using both sets of *t-z* curves (full and reduced gauge sets) as input into a Microsoft Excel implementation of the *t-z* analysis (Meyer, Holmquist, and Matlock 1975) generates the two equivalent top load curves plotted in **figure 6**. The curves in the figure are normalized because the purpose is to illustrate the difference between using 25 and 9 *t-z* curves, not to document the actual load-settlement behavior of this particular test pile. Although the equivalent top-loading curves generated using 25 and 9 curves are not an exact overlap, their differences are most likely due as much to the limitations of the iterative numerical solution of the *t-z* model as they are to information loss in the reduced level data set.

Conclusions and Recommendations

The use of strain gauges in deep foundation testing can yield very useful information, but as is often the case, more is not necessarily better. A straightforward error analysis demonstrates how the horizontal arrangement of gauges can be optimized to achieve a high statistical reliability while ensuring the results represent the average axial strain. By using this result, the vertical arrangement can then be optimized, reducing the number of redundant levels of gauges in any particular soil stratum while maintaining confidence in gathering the information needed for design.

The case history pile test discussed in detail in this article consumed a total of 72 strain gauges. Using the gauge arrangements proposed herein (4 gauges per level at 8 levels) yields a very similar result in terms of assessing force distribution and equivalent top-down load-settlement behavior, with greater reliability, using only 32 gauges.

Test program specifications often call for gauges at evenly-spaced depths. Using applicable nearby (ideally, on-center) borings to help identify desired gauge placement is almost always a more efficient use of the available gauges than prescribed spacing. Such a boring may not be available until very near the installation date for the test pile because of site access. However, the actual mounting of gauges to the pile reinforcement cage is relatively quick and often the last activity to take place prior to pile installation. Although specifications and contracting needs may dictate the total number of gauges well ahead of time, close coordination between the design engineer, contractor, and test engineer can be used for just-in-time location of gauges for optimal test results.

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